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Measuring Human Performance in a Mobile Ad Hoc Network (MANET)

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Tactical warfighter networks represent the final leg of the Network Centric Warfare space to mud continuum. The challenges associated with developing, evaluating, and fielding these networks are significant, as experience from field evaluations demonstrates. Even more critical is the capability to quantitatively measure the extent to which tactical networks serve the Warfighters who depend on them for data and information. Such analysis is constrained in two respects. The first is the lack of measures for the reliable correlation of human performance to network Quality of Service levels. The second is the lack of applied data collection methodologies for objective analysis of timeliness and accuracy of decision inputs in the context of integrated Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance networks. This article reports on research applications addressing both issues. Our findings were developed over a 5-year period from experience in a tactical networked operations field test environment. We describe a methodology for the reliable collection of human situational awareness measures and report human performance findings in the context of network metrics. We suggest emerging linkages between human and network performance metrics. Our conclusions recommend future actions that will support user-centric test and evaluation of tactical networks, systems, and networked Command and Control.

Key words: Decision accuracy; decision timeliness; human performance; mobile ad hoc network; situational awareness; work load.

The first decade of the new millennium saw an avalanche of research in Network-Centric Warfare (NCW).[1] Much of the early research and lessons learned from current operations focused on the strategic and operational levels of command (Conner 2005), where the four tenets of NCW (Office of Force Transformation 2005) were somewhat easier to address compared with the more mobile tactical force:

1. A robustly networked force improves information sharing.
2. Information sharing enhances the quality of information and shared situational awareness.
3. Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
4. These, in turn, dramatically increase mission effectiveness.

The relative ease of analysis at the higher command echelons (e.g., Joint Operations, Coalition Air Operations Centers) is determined in most part from the stable networks that are utilized in these settings to link centralized and remote nodes that are stable in terms of location and satellite links. If viewed from the lens of the tactical echelon, however, the four tenets of NCW are less intuitive, highly dependent on the variable performance features of Mobile Ad Hoc Networks (MANETs), and require adaptive Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) human system interface capabilities that can mitigate the MANET drop-off/self-healing node design. For example, in his analysis of the Operation Iraqi

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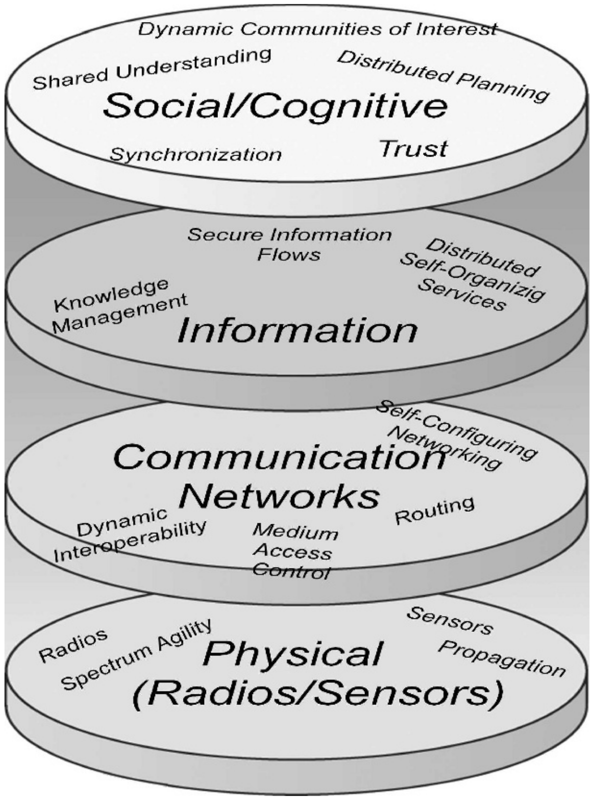

Figure 1. Network component levels (NRC 2005).

Freedom 2003 Thunder Run (where lead elements of the 2nd Brigade, 3rd Infantry Division attacked Baghdad from the southern outskirts, through the city and west to the airport [Conner 2005, p. 15]), Conner noted that carrying the "robust intelligence capability [through a common operating picture] forward to the tactical level would prove almost completely lacking" (p. 18). He characterized the existence of a "digital divide" between operational and tactical commands and suggested that the reasons for this divide were the great distances covered by tactical units and the vast amount of data they were attempting to share. Conner notes several examples in the early phase of Operation Iraqi Freedom where "the promise of technology providing near perfect situational awareness had failed the tactical commander" (p. 20).

Our central thesis is that productive research in the realm of tactical networking must focus on linking the physical, information, communications, and cognitive/social dimensions of the network. Intuitively, this is a sound assertion; human performance should always be investigated *in the context* of supporting technologies. Practically, this is a large challenge in terms of choosing metrics for comparison and in collecting data for analysis. This point is easily made by examining the representation of the network levels in *Figure 1* (National Research Council 2005). If we were to choose one metric from each level that could be expected to cluster, we might choose propagation (Physical), routing (Communication), secure information flows (Information), and shared understanding (Social/Cognitive). The first three metrics could be quantitatively measured, and we could develop correlations among these results. However, no quantitative metric is available for shared understanding suitable for correlation with the Quality of Service (QoS) metrics. In addition, MANET performance is designed to be dynamic, with nodes dropping off and self-healing due to terrain and weather conditions. This performance is invisible to the human eye; users must detect network anomalies from characteristics such as latency of communications, failed messages, or garbled radio speech. Also, unlike the QoS measures, human performance measures such as shared understanding will be degraded for several reasons; network performance is only one contributor. Experience, training, workload, and fatigue provide additional factors that contribute to shared understanding. Partitioning out the variance in this factor due to network performance adds complexity to the human-network analysis problem. As we address this issue, we briefly consider the network environment that serves as the setting for our research.

U.S. Army tactical networks will be MANETs, characterized by wireless radios with limited bandwidth and no fixed infrastructure support. Instead of fixed network nodes, the MANET nodes will be dynamic; they will enter and leave the network at any time due to mobility and terrain conditions (Chiang et al. 2008; Ikeda et al. 2009). In MANETs, network nodes will include vehicles, dismounted soldiers, and unattended sensors and unmanned vehicles. The challenges associated with developing information and communication systems that can operate on a MANET are far from trivial. Porche, Jamison, and Herbert (2004) used a high-resolution simulation to model variations of communication and network parameters to determine the impact on battle command displays. For example, these authors determined that if sensor inputs were limited to 50 percent of the run time, and Common Operational Picture (COP) update rates were no more than once per minute, message completion rates could be above 75 percent. Notably, no human-in-the-loop testing was used to determine the effect of these parameters on decision making. For example, COP update rates of once per minute would be acceptable for a static force, if that force were moving; however, such a rate would be insufficient for navigation from the COP.[2] Simulations are useful in network performance testing because of

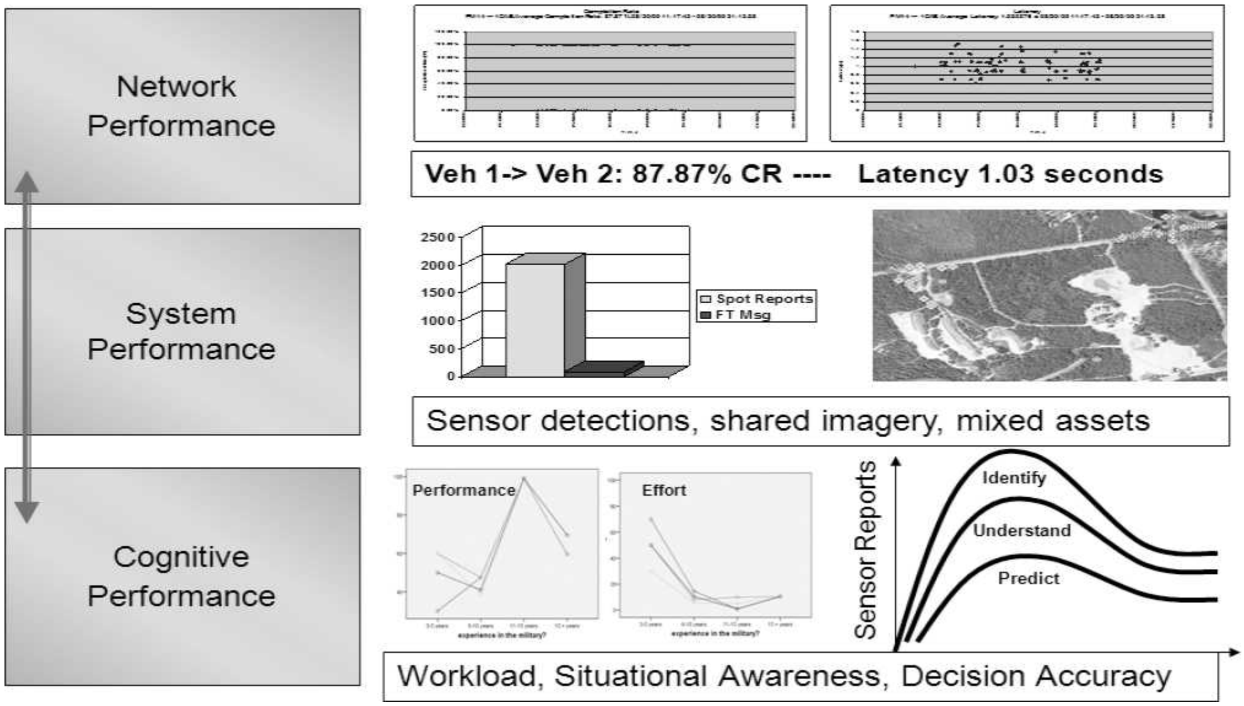

Figure 2. Schema for measuring cognitive performance in context of system and network performance.

the unpredictable and dynamic nature of MANETs in open terrain conditions. They have been used for a variety of performance testing, such as packet latency (Anna and Bassiouni 2006), wireless communication protocols (Gao and Boscardin 2006), and cross-layer routing (Iannone, Kabassanov, and Fdida 2007). These authors, respectively, systematically varied traffic rates for system load and data packet sizes (Anna and Bassiouni), network density and protocol performance (Gao and Boscardin 2006), and hop-count rate and transmission rate (Iannone, Kabassanov, and Fdida 2007). These evaluations provide a foundation for field experimentation in that they support the development of physical MANET capabilities and document simulated network performance bounds.

Field experimentation of human-in-the-loop experiments on MANETs is complex from several perspectives. First, the very nature of MANETs makes controlled variation of key factors difficult. MANET structure and performance (e.g., connectivity, node links, bandwidth, message completion rates) is dynamic by design and cannot be easily controlled. This inability to systematically vary performance parameters presents a challenge to hardware, software, and human evaluation efforts (Bowman and Kirin 2006; Porche, Jamison, and Herbert 2004). Relating human performance to specific network and system characteristics is a second challenge. For example, consider the example described above from the Porche, Jamison, and Herbert simulation. What quantitative impact would a 50 percent sensor feed, a 1-minute COP update, and a 75 percent message completion rate have on workload and situational awareness? Further, what impact would those levels of workload and Situational Awareness (SA) have on timeliness and accuracy of decision making? These questions imply a third challenge: measuring human performance in objective and quantifiable ways with tools and techniques that can be applied across a range of systems, experiments, and evaluations. Partial solutions to these challenges have been developed by the authors over a 5-year period. In that time we have produced meaningful conclusions in the realm of the cognitive impact of networked C4ISR technologies on battle command performance at the tactical level.

The schematic in *Figure 2* provides a high-level view of our efforts to integrate performance metrics across the network (Physical and Communications), the System (Information), and Cognitive (Social/Cognitive) domains. This diagram shows excerpts from our data collection methodology. Network performance shows Message Completion Rates (MCR) and latency of messages. System performance shows numbers of spot reports and free text messages sent during the mission, and shows a COP screen shot of sensor spot reports (the yellow clover leaves). Cognitive performance shows variable levels of workload in terms of performance satisfaction and effort expended and three

levels of SA over time. This schematic shows data for one record run when the network was performing quite well (high MCR and low latency). This high network performance is borne out by the high number of spot reports (over 2,000) and free text messages (87), substantiated by the COP screen shot (yellow icons fade out after 5 minutes). The resulting sensor icons appearing automatically on the display explains the spike in workload and the initially high levels of SA, followed by diminishing SA as the spot reports became too numerous to track. This example of the impact of network and system performance on human performance provides a view to our study objectives. In the remaining sections of the article, we delve into the network and cognitive levels in more detail. We do not address system performance in this article.

The remainder of this article is organized as follows. We provide a brief description of the venue in which our measures and methodology were developed. We then illustrate the data collection methodology that has proven useful for our purposes as detailed above. Next, we review the network and human performance measures used in our analysis. Finally, we offer conclusions that can extend our work for test and evaluation analyses of tactical networks and system-of-systems applications.

Historical perspective: C4ISR On The Move (OTM)

Since 2005, we have engaged resources at the annual Communications Electronics Research, Development, and Engineering Center (CERDEC) C4ISR OTM experiments to determine how tactical soldiers will benefit from an integrated sensor and communications suite to improve timeliness and accuracy of decision making. At this venue, soldiers use instrumented vehicles and various mounted and dismounted communications devices, interact with unmanned air and ground vehicles and unattended ground sensors, and view Battlespace entities on a COP that is an enhanced version of Force XXI Battle Command Brigade and Below (FBCB2).[3] Annually, a range of C4ISR technologies are integrated in a tactical network for soldiers to use against live Opposition Forces (OPFOR) (PM C4ISR OTM 2005; PM C4ISR OTM 2006; PM C4ISR OTM 2007; PM C4ISR OTM 2008; PM C4ISR OTM 2009). Soldiers operated in operationally relevant missions daily against a live, but scripted, enemy force. All enemy forces (vehicles and personnel) were also instrumented. This important capability is further described in the following section.

Our early efforts at documenting the cognitive impact of an integrated and networked sensor suite depended on a large force of human data collectors to observe soldiers at multiple node locations and to administer surveys at strategic points in the runs (PM C4ISR OTM 2005; PM C4ISR OTM 2006; PM C4ISR OTM 2007). Although we triangulated our data collection (Cresswell 1998) with multiple inputs (observation, survey, individual and group interviews), we determined that a field study of this type demanded novel methods that were less human-intensive and intrusive into the soldiers' experiences (Bowman and Kirin 2006). In subsequent years, we modified the Army SALUTE (Size, Activity, Location, Unit, Time, Equipment) report to include two subsequent fields: Assessment and Prediction. The subsequent SALUTE-AP survey was an effective tool to extract SA reports from soldiers, but it still required human intervention and Subject Matter Expert (SME) scoring of reports (Bowman and Thomas 2008, 2009). The SALUTE-AP tool also restricted SA findings to enemy-specific information; no awareness of own forces was included. And, while the SALUTE-AP represented an improvement, it was still a subjective report. We continued to search for objective measures that would serve to support the subjective reports. The Geospatial Environment for Command and Control Operations (GEC2O)[4] visualization tool finally provided the analysis medium for which we had been searching.

Methodology

GEC2O

The GEC2O tool was designed originally as a Rapidly Operational Virtual Reality (ROVR) system to provide a large-scale three-dimensional (3-D) immersive visualization environment. The system allows users to interact with terrain models from Google Earth as well as high-fidelity models created by the developers. The modeled terrain provides extremely accurate representations of wooded and urban training ranges at Fort Dix where missions were conducted. Map overlays, which can be easily printed for later use, are created using standard drawing tools and embedded 2525B military symbology. The ROVR supported both virtual walk-through and flyover navigation through its modeled terrain. It received and stored all FBCB2 tactical messages and unit position information transmitted over the tactical local area network, which was viewable in real time or later via playback. The ROVR was installed in the Tactical Operations Center and configured using two 6- by 4-foot rear projection screens for an overall footprint of about 12-feet wide by 7-feet high by 8-feet deep. The soldiers used this capability infrequently in early years due to the remote location of the large screen display. Typically, they used rock drills as shown in *Figure 3*.

Figure 3. Rock drill, Geospatial Environment for Command and Control Operations (GEC2O) display, and GEC2O mission planning.

Also in *Figure 3* are the large display and a slightly smaller 3-D version used for planning.

In 2008 and 2009, the GEC2O developers provided the visualization capability on a smaller flat screen and a tabletop display as shown in *Figure 4*. The overlays created in GEC2O were electronically uploaded into FBCB2 in the vehicles. With these technologies, the rock drills with sticks and pinecones became a phenomenon of the past.

A feature of GEC2O that enabled it to be used as an analysis tool is the ingestion of instrumented position reports, sensor spot reports, and free text messages for geospatial and time-stamped display. In 2008 and 2009, we used the GEC2O to provide objective analysis of subjective reports of SA, and discontinued the SALUTE-AP surveys (though we did continue to administer surveys to record workload, trust in network, and usability concerns for technologies). We also continued a short, four-question survey on SA in order to provide context to our objective SA findings.

Prior to the daily mission runs, the soldiers were instructed to send SALUTE reports through their FBCB2 free text messaging system whenever they learned of new enemy activity. Since these were captured and time-stamped in GEC2O, they provided us an archive of such reports. By viewing the map display with Red and Blue icons (vehicles and dismounts), we could substantiate the SALUTE reports to determine accuracy of Size, Location, and Time elements of the report. For Activity, Unit, and Equipment, we relied on the script for the enemy runs and for records of activity maintained by the lead analyst assigned to the enemy force. We were also able to assess timeliness of reports through the time-stamps in the GEC2O system. We compared the message received time with the XML time sent to calculate network travel time for the message. In addition, we were able to impute some system performance variables in the human decision-making calculus. For example, in GEC2O, sensor spot reports are displayed as yellow cloverleaves. In *Figure 5*, the display shows one sensor field providing many reports while another field (marked by the red circle in the middle of the map) provides none. Therefore, enemy vehicles approaching through the inactive sensor field would arrive undetected, whereas those arriving through the overactive field could be undetected due to the soldiers' inability to integrate a high number of redundant reports.

GEC2O analysis of decision-making accuracy and timeliness

Timeliness and accuracy of decision making were analyzed with one representative day's retrospective review of data from GEC2O playbacks. This was an

Figure 4. Geospatial Environment for Command and Control Operations tabletop display and 2-D flat-screen display.

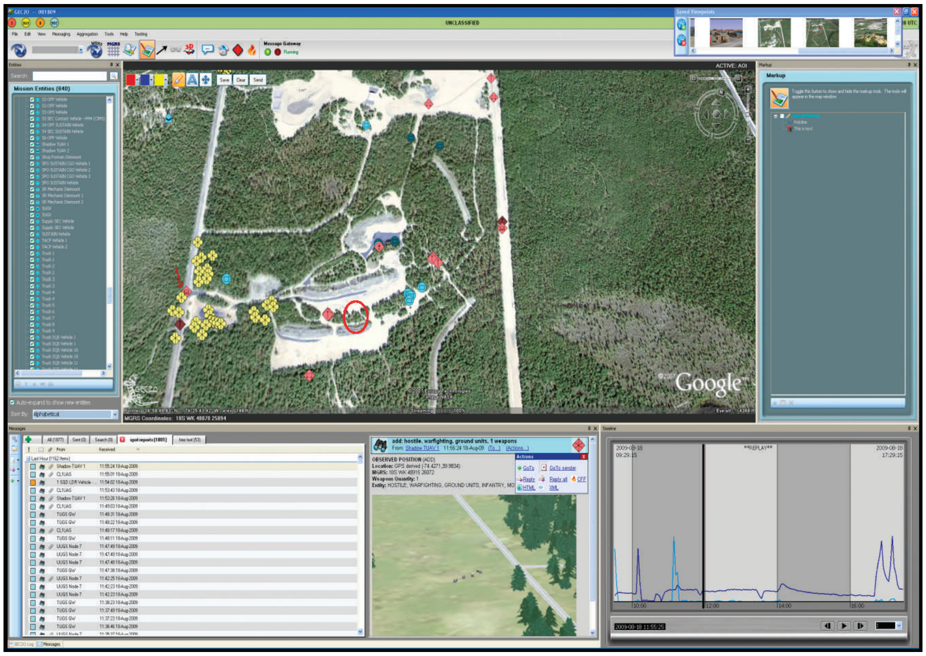

Figure 5. Geospatial Environment for Command and Control Operations screen shot.

exploratory methodology and was not undertaken for each day's record runs. The run from August 20, 2009, was chosen for analysis because it provided a good selection of network, system, and human performance data points. On this date, 12 separate messages were investigated. These messages are shown in *Table 1*. In this table, we have extracted the relevant features of the message contents as well as our analysis findings. The messages extracted for analysis were all free text messages sent from one soldier (usually the Squad Leader) to the group of soldiers, all located in stationary vehicles. The messages were generally uniform in composition and size and contained text that communicated that soldier's knowledge of enemy activity, location, and size. The messages were evaluated for timeliness and accuracy according to low, medium, and high scores. High scores for these measures reflect reports that contained activity descriptions that were very close to ground truth (accuracy) and took little time to process (timeliness). The time delays reported in this analysis reflect network transit time, not time delays due to human activity.

The latency rates were calculated in the following way. Each message received in the GEC2O system showed a "received" time and a "sent" time. The latter was available in the XML script showing the message properties. The analyst subtracted the received time from the sent time to calculate latency. Review of message latency times shows that latency was variable in the mission run; messages were delayed significantly in the early portion of the run but experienced very low latency throughout most of the remainder of the mission. Latency began to rise again at the end of the trial runs. This characterization of tactical network performance shows the influence of the airborne communications relay. On each day, the airship had to travel from the nearby airport to the test site. The early and late messages with high latency reflect message traffic that used ground, rather than airborne, relay mechanisms. Also, even when the airship was present, it sometimes experienced problems that affected the vehicle network. For example, if the airship was not at a high enough altitude to affect the communications relay, ground network pathways were used, resulting in network delays.

Decision accuracy

Decision accuracy was measured on a low-medium-high scale based on the soldier's description of enemy location and activity compared with ground truth. Ground truth was ascertained from the GEC2O playbacks of the instrumented OPFOR vehicles and personnel. Because these position reports were captured locally and manually collected after each mission, these reports are accurate on the display to within 10 meters. This position accuracy is compared with the BLUE position reports that are transmitted via the satellite network and are accurate to within 20 meters. The BLUE reports noted in *Table 1* contain information that the soldiers extracted from various sensors, including soldier visual detections, unmanned aircraft system (UAS) imagery, and simulated Unattended Ground Sensor (UGS) sensor reports. The UAS and UGS reports included a 10-digit grid location of the

Table 1. Decision accuracy and timeliness measures August 20, 2009.

Time of report	Time delay (s)	Description of report	SME interpretation of report	Score: Accuracy	Score: Timeliness
1029	349	Reported 4 vehicles with grid location	Grid location within 14 meters of enemy vehicle	High	High
1040	131	Reported 4 moving vehicles	Only 1 was mobile, 3 were stationary	Medium	Medium
1045	103	1 Vehicle reported at grid location	Grid location was within 36 meters of vehicle	High	Medium
1117	20	Reported 11 dismounts at grid location (based on simulated spot report with grid ID)	Grid location was exact	High	Low
1125	17	Reported 1 vehicle and 1 dismount (based on simulated spot report with grid ID)	Grid location was exact	High	Low
1129	21	Reported 1 stationary vehicle (based on UUGS spot report)	Grid location was exact	High	Low
1135	19	Reported 1 stationary vehicle (based on UUGS spot report)	Grid location was exact	High	Low
1146	23	Reported 1 dismount walking south from grid location (based on UAS image)	Grid location was within 10.57 meters	High	Low
1151	21	Reported 1 vehicle driving (based on UUGS spot report)	Grid location was exact	High	Low
1201	21	Reported 1 stationary yellow sedan with grid location (based on DCGS-A image)	Grid location was exact	High	Low
1214	20	Reported 1 stationary vehicle and 1 dismount	Grid location was exact	High	Low
1215	80	Call for fire on yellow sedan (based on simulated spot report with grid ID)	Grid location was exact	High	Medium

SME, subject matter expert; ID, identification; UUGS, urban unattended ground sensors; UAS, unmanned aircraft system.

target. All of the UAS sensor reports and some UGS sensor reports included a simulated image (see *Figure 6* for examples of simulated images).

As might be expected, the soldier messages of enemy activity that were based on the simulated sensor reports were highly accurate. It is clear why the soldiers were so accurate using simulated sensors; the images are very clear, and the reports contain 10-digit grid locations of the OPFOR (e.g., in *Figure 6*, the image of the burning vehicle shows a grid location of 18 S WK 50105 24717).

Decision timeliness

Decision timeliness was also measured on a low-medium-high scale, with low ratings being the more preferred state. The timeliness ratings for each message are shown in the second column of *Table 1*. These results show a consistent trend in the message timeliness factor noticed by experiment observers over the 3 weeks of the experiment. The initial report required 349 seconds to reach the GEC2O system; this was followed by rapidly descending time periods until the last message, which began to increase in time required to transit the network. The curve of message latency is shown in *Figure 7*.

It is at this point that the difficulty in analyzing cross-domain measures comes into play. When we sought to understand the reasons behind message latency, we learned that the network engineers had a different perspective on that network performance metric. The latency measures recorded by the network engineers are presented in *Figure 8*. Comparison of the

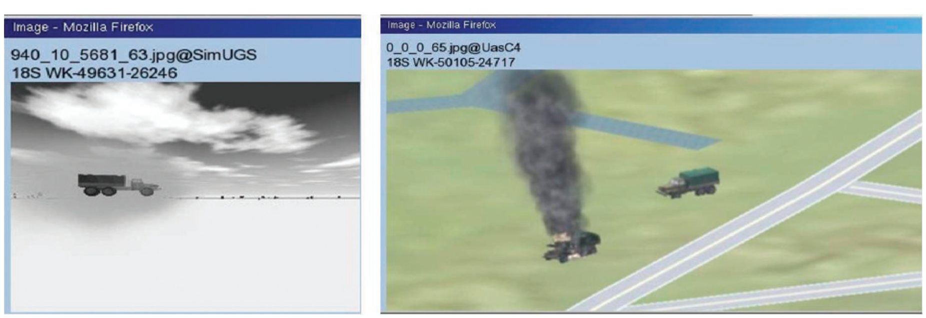

Figure 6. Simulated sensor images (Unattended Ground Sensor on left and a Class IV UAS on right).

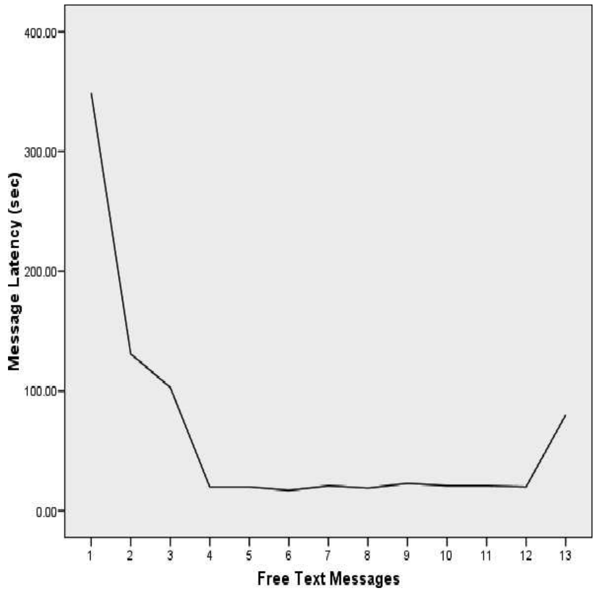

Figure 7. Visual display of message latency in seconds.

latency metrics shows a best (e.g., lowest) latency of 19 seconds in *Figure 7*, but a best latency of less than 1 second in *Figure 8*. We believe that this represents a difference between network level and application level measurement; however, this was not confirmed by the network engineers.

Figure 8 shows the average latency of messages as recorded by the automated network data collection tools. The one consistency between *Figures 7 and 8* and *Table 1* is the spike at 14:52:48 shown in *Figure 8* and the 349 second latency in *Table 1*, row 1. The network times were recorded in Greenwich Mean Time (GMT), which was a 4-hour additive time from the GEC2O recording format (Eastern Daylight Time). It appears that the network latency recorded a large spike at approximately the same time period as the message latency in the application layer of GEC2O. Though these latency figures are far from equal (349 seconds vs. 36 seconds), the same phenomena appear to affect both

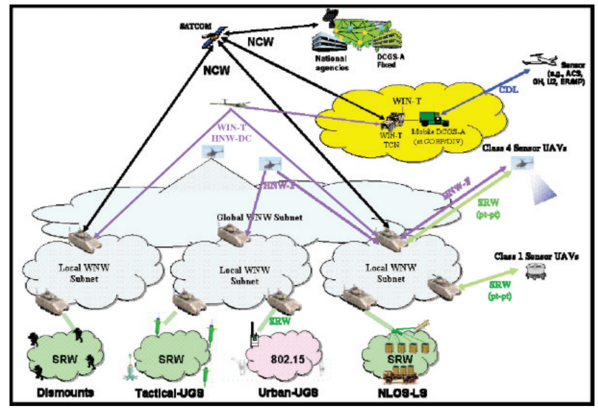

Figure 9. Future combat systems (FCS) multi-tiered transport architecture.

systems. We believe that the inverted bell-shape curve, displayed in *Figure 7*, is the result of several confounding issues. Some of the issues include network delays at the beginning and end of the record runs, message-processing delays on the GEC2O system because of volumes of simulated position reports, a delay in message arrivals due to GEC2O system re-booting during a mission, and differences in time synchronization between the GEC2O system time and the network time. Those differences are under investigation by a joint team of analysts from CERDEC Command and Control Directorate, PM C4ISR OTM and the Army Research Laboratory, and serve to point out the difficulties in this type and level of analysis. We will now shift our discussion to cover the cognitive and network measures used in our analysis.

Measures: cognitive and network performance

The emphasis on investigating the cognitive impact of an integrated C4ISR suite of technologies was driven by the understanding that warfare will always be a human activity. Technology must support human decision making, but it will never replace it. The drive

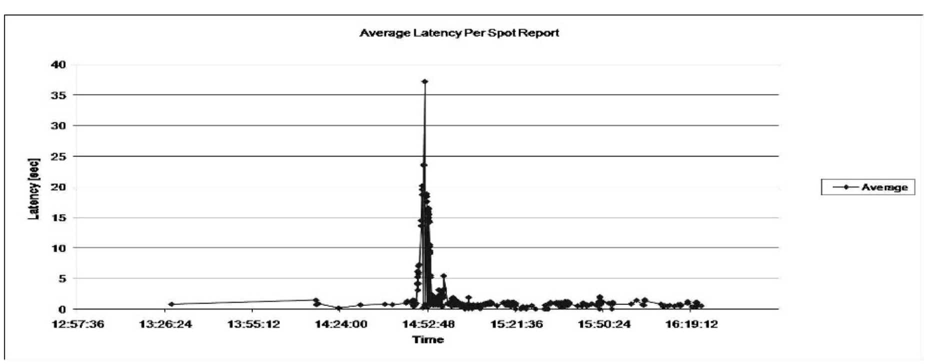

Figure 8. Average latency per report.

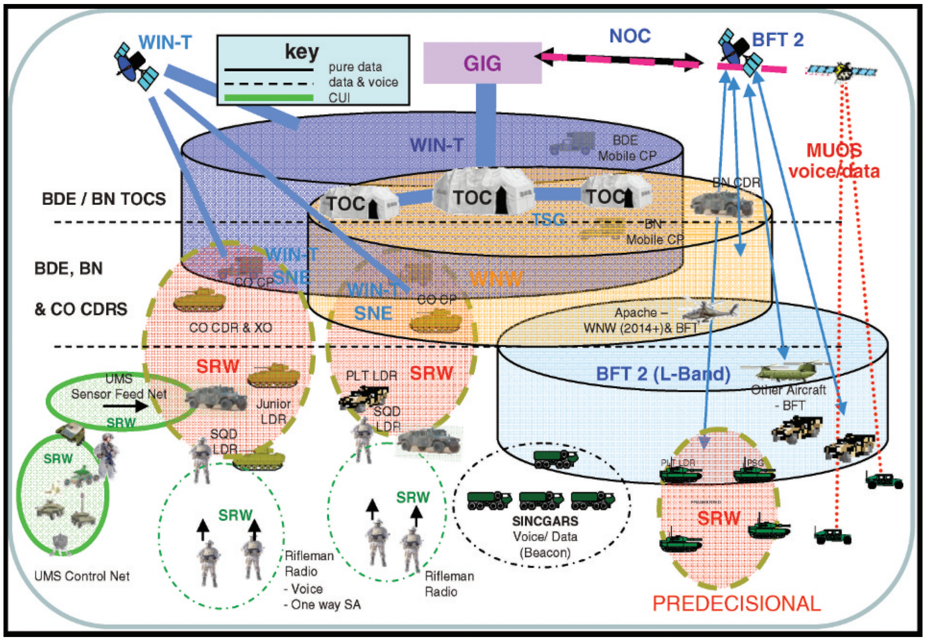

Figure 10. 2013 Modular brigade combat team architecture.

to develop sophisticated decision support systems and intuitive visual displays must include consideration for the ways in which soldiers will utilize these systems on the battlefield. Networked C2 places the human Warfighter at the center of a complex, dynamic, and uncertain web of information. This study measured the impact of networked human and sensor information on the cognitive performance of soldiers at the tactical level. This study provided a benchmark for future analysis of how valid the basic network centric warfare tenets may be for the tactical Warfighters. In the next section, we briefly introduce the network architecture that supported these capabilities and review network performance measures. We follow this discussion with cognitive measures.

Network architecture design

The architecture design elements of the 2009 study were drawn from several including the Future Combat Systems (FCS) Multi-Tiered Transport Architecture, the Unified Battle Command 120 Day study (Moore 2008) and the 2013 Modular Brigade Combat Team (MBCT) Architecture (Latham 2008). Each of the communications architectures employed a variety of systems depending upon the specific configuration under examination, as shown in *Figures 9 and 10*.

Within these architectures, a common element includes satellite communications provided by the NCW, which support an on-the-move satellite capability. NCW is a communications waveform that acts as the primary satellite mechanism for Increments 2 and 3, as well as being available for technology insertion at Increment 1. NCW is an Internet Protocol (IP)-based, bandwidth-on-demand protocol that supports block file data, voice, and video services, as well as other IP-based services to support disadvantaged terminals that may have smaller dish sizes, rendering them less capable. In addition, Soldier Radio Waveform (SRW) is common to both architectures. SRW is an IP-based, software-defined digital communications waveform that supports voice, data, and video services. SRW is designed to provide communications to dismounted soldiers, unattended ground sensors, intelligent munitions systems, non-line-of-sight launch systems, and unattended ground and air vehicles.

Network performance

Several tables are presented to illustrate the performance of the network during the C4ISR OTM 2013 MBCT platoon trial runs. *Table 2* represents the view of network performance from the Brigade Headquarters' perspective. The tables were derived from the daily data sets that were harvested after the completion of the runs. These data include any unicast data between C4ISR Information Management System (CIMS) and FBCB2s, as well as any multicast data that originated either from FBCB2 or CIMS. These multicast groups include the standard groups for CIMS Gateway messages, which include imagery notifications, imagery request, imagery transfers, and chat.

The primary focus of our attention in these network performance metrics is the lowest tactical leader—the

Table 2. Network performance – Brigade Headquarters view.

		August 14, 2009 1337–1653		August 18, 2009 1311–1757		August 20, 2009 1313–1630		August 21, 2009 1717–2000	
Radios	**From the BDE HQ to**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**
NCW	CO CDR	76.9%	0.60 s	77.5%	0.45 s	95.8%	0.60 s	89.4%	0.59 s
SRW CO Net	VPL1	12.7%	0.95 s	69.1%	1.31 s	87.3%	1.80 s	88.0%	1.32 s
SRW CO Net	VPL2	12.5%	0.95 s	69.1%	1.13 s	87.1%	1.80 s	89.2%	1.33 s
SRW CO Net	PL	66.3%	0.78 s	58.2%	0.73 s	76.9%	0.83 s	82.0%	0.85 s
SRW PLT Net	SL	65.3%	1.00 s	55.6%	0.96 s	75.4%	1.00 s	76.8%	1.00 s

BDE, brigade; HQ, headquarters; NCW, network-centric warfare; CO, company; CDR, commander; s, seconds; SRW, soldier radio waveform; VPL, virtual platoon leader; PL, platoon leader; PLT, platoon; SL, squad leader.

Platoon Leader (PL). These performance metrics presented in *Table 2* show that the MCRs for messages coming from the Brigade Headquarters to the PL ranged from 58.2 percent to 82 percent, with latency measures of less than 1 second.

The network performance metrics from the Company Commander to the PL on the same dates *(Table 3)* show better MCRs; the range of MCR was 60.7 percent to 97.1 percent. We note that only 1 day had a lower than 87 percent MCR, however. Again, latency was a non-issue, with scores in the less than 1/4-second range.

The PL perspective, shown in *Table 4*, shows fairly positive network metrics from the MCR and the latency categories. On August 14, 2009, the PL had low MCRs with the Virtual Platoon Leaders 1 and 2, but these scores rose on the remaining days. The completion rates from the PL to his Company and Brigade Headquarters ranged from the mid-80s to mid-90s range, with low latency in all cases.

A comparison of the network performance for these seven trials offers a mix of both expected and some unexpected results. The network, composed of NCW and SRW, yielded a completion rate of 74.8 percent. This result indicates that just under three quarters of the messages sent during the trials actually reached their intended recipient, yet the soldiers were generally able to complete their assigned missions. These results do not suggest that a 75 percent message completion rate is acceptable but rather illustrates how adaptive the soldiers were in accomplishing their missions despite network performance issues. For example, when the soldiers were not receiving the reports or messages that they were expecting, they would use the provided voice communications, either Single Channel Ground and Airborne Radio System (SINCGARS) or SRW, to send or request the needed information. If they were unable to reach the intended person on the radio, they would frequently rely on personal cell phones to send text messages and images of the OPFOR. Finally, when other means of communication were unavailable, the soldiers would simply drive to the other person's location and conduct a face-to-face meeting. These results do not imply that "alternate" means of communication were preferred by the assessment team; rather they demonstrate the ingenuity of the participating soldiers to work around the limitations of the experimental network. The next section will describe the impact of the technologies on soldier performance.

Table 3. Network performance – Company Commander view.

		August 14, 2009 1337–1653		August 18, 2009 1311–1757		August 20, 2009 1313–1630		August 21, 2009 1717–2000	
Radios	**From the CO CDR to**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**	**Completion rate**	**Average latency**
NCW	BDE	90.0%	0.74 s	76.7%	0.72 s	75.9%	0.60 s	67.8%	1.37 s
SRW CO Net	VPL1	35.4%	0.44 s	71.6%	0.39 s	78.1%	0.76 s	88.4%	0.65 s
SRW CO Net	VPL2	36.3%	0.44 s	70.6%	0.32 s	77.7%	0.80 s	88.4%	0.65 s
SRW CO Net	PL	97.1%	0.18 s	87.0%	0.18 s	60.7%	0.21 s	94.2%	0.21 s
SRW PLT Net	SL	95.2%	0.39 s	78.3%	0.38 s	59.5%	0.44 s	90.7%	0.42 s

CO, company; CDR, commander; NCW, network-centric warfare; BDE, brigade; s, second; SRW, soldier radio waveform; VPL, virtual platoon leader; PL, platoon leader; PLT, platoon; SL, squad leader.

Table 4. Network performance – Platoon Leader view.

Radios	From the PL to	August 14, 2009 1337–1653		August 18, 2009 1311–1757		August 20, 2009 1313–1630		August 21, 2009 1717–2000	
		Completion rate	Average latency	Completion rate	Average latency	Completion rate	Average latency	Completion rate	Average latency
NCW	BDE HQ	81.0%	0.92 s	69.5%	1.09 s	83.4%	0.87 s	77.9%	1.50 s
SRW CO Net	CO CDR	85.2%	0.16 s	96.7%	0.22 s	82.4%	0.32 s	96.2%	0.24 s
SRW CO Net	VPL1	22.6%	0.32 s	72.4%	0.26 s	88.8%	0.91 s	82.4%	0.55 s
SRW CO Net	VPL2	20.6%	0.34 s	71.0%	0.29 s	87.7%	0.98 s	84.4%	0.55 s
SRW PLT Net	SL	98.2%	0.23 s	69.8%	0.22 s	96.9%	0.22 s	92.1%	0.23 s

PL, platoon leader; NCW, network-centric warfare; BDE, brigade; HQ, headquarters; s, second; SRW, soldier radio waveform; CO, company; CDR, commander; VPL, virtual platoon leader; PLT, platoon; SL, squad leader.

Table 5. Confidence in computer use.

Survey question	Mean	Standard deviation	Minimum	Maximum
I am confident in my ability to use computers in general.	4.8	.41	4.0	5.0
I am confident in my ability to use Army C2 digital systems.	4.0	.89	3.0	5.0
I am confident in my ability to learn to use new software quickly.	4.5	.55	4.0	5.0
I am confident in my ability to perform multiple tasks at the same time.	4.7	.52	4.0	5.0
I am confident in my ability to use personally owned computers.	4.8	.41	4.0	5.0

Cognitive performance measures

Demographics

Soldier participants in this study included five Noncommissioned Officers (NCOs) from the New Jersey Army National Guard (NJ ARNG) and one Officer from CERDEC. All study participants were male. These soldiers were assigned roles as the Company Commander, Platoon Leader, Platoon Sergeant, Squad Leader, and Robotics operators. The NJ ARNG soldiers had returned from a year-long combat deployment earlier in the summer. The rank of the soldiers was Major (1), Sergeant First Class (1), Staff Sergeant (2), and Sergeant (2). The soldiers represented a range of experience in the military. Due to the small number of participants, experience levels were divided into less than and more than 10 years of service.

We documented the soldiers' subjective perception of their ability to use computer systems because the Unified Battle Command study revolved around digital battle command displays. *Table 5* displays these data. The questions were measured on a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). On average, the soldiers were extremely confident in their ability to use computers in general, to use personal computers, to perform multiple tasks at the same time, and to learn new software quickly. Slightly lower scores were recorded for the confidence in using Army C2 digital systems. The mean score of 4.0 (standard deviation [SD] = .89) represented two soldiers who rated this question as "neutral," two who "agreed," and two who "strongly agreed."

Workload

Within the network configuration described above, four record runs were achieved from August 18–21, 2009. A repeated measure Multivariate Analysis of Variance (MANOVA) was used to analyze these data. Though some minor differences in workload were noted in the two experience groups, none of these differences are significant at the $P = .05$ level. As can be seen in *Figure 11*, the less experienced soldiers consistently reported slightly higher workload levels than did their more experienced counterparts. However, the highest level of workload reported was achieved on day four of this MBCT trial, and that mean score was 38.04, SD = 10.36. Considering the scale of the workload measure (0–100), this was a low workload rating.

Situation awareness

A repeated measures MANOVA was used to analyze these data, which are graphically displayed in *Figure 12* by day. On each day, the less experienced soldiers reported that they experienced more difficulty than their more experienced counterparts in achieving Levels 1, 2, and 3 SA, but these differences were not significant. It should also be noted that this amount of difficulty, though relatively higher than the more experienced soldiers, is still rather low. That is, none of

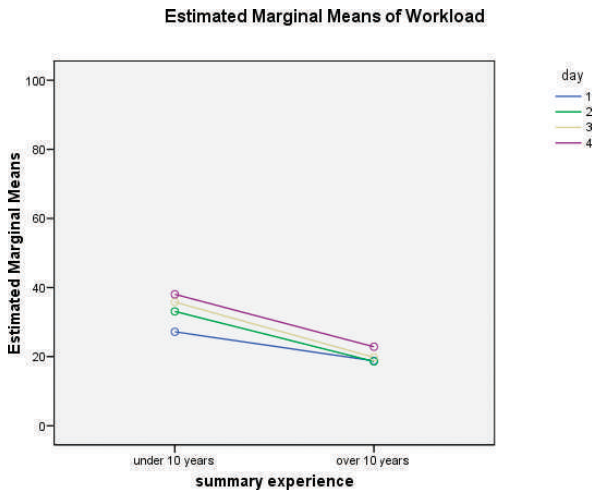

Figure 11. Average workload by experience level in modular brigade combat team.

the soldiers reported much difficulty in achieving SA at all levels.

Conclusions

This report documents a number of major contributions to tactical networked battle command engineering and soldier performance challenges. The vision of Unified Battle Command provides an evolutionary path for the integration of dissimilar applications, communication and sensor technologies, and forces in full spectrum operations. The C4ISR OTM Unified Battle Command Cognitive Impact Study (UBC-CIS) explored the major tenets of this vision. The findings enumerated in this report validate the fundamental assumptions of UBC and clarify technology and human challenges in realizing networked command and control at the lowest tactical echelon.

The network architecture developed for the UBC-CIS provides a firm foundation for continued test and evaluation of networked communication and sensor technologies for tactical elements. Specifically, the 2009 architecture confirmed that multiple pathways (air-satellite-ground) for data transmission are feasible with quantifiable QoS consequences for each route. These QoS impacts (latency, message completion rates) were correlated with human situational awareness and decision making. Knowledge of lesser collaboration pathway consequences can be used by commanders to select, in advance, pathways based on mission requirements and technology availability.

This study also examined technology and human performance factors to investigate the feasibility of extending the network to the lower tactical elements. From a technology perspective, challenges were documented in maintaining connectivity with mobile and static vehicle configurations in forested and open terrain. Soldiers derived adaptive ways of sharing information with less advantaged members of the unit. Redundant communication modes were essential to this capability.

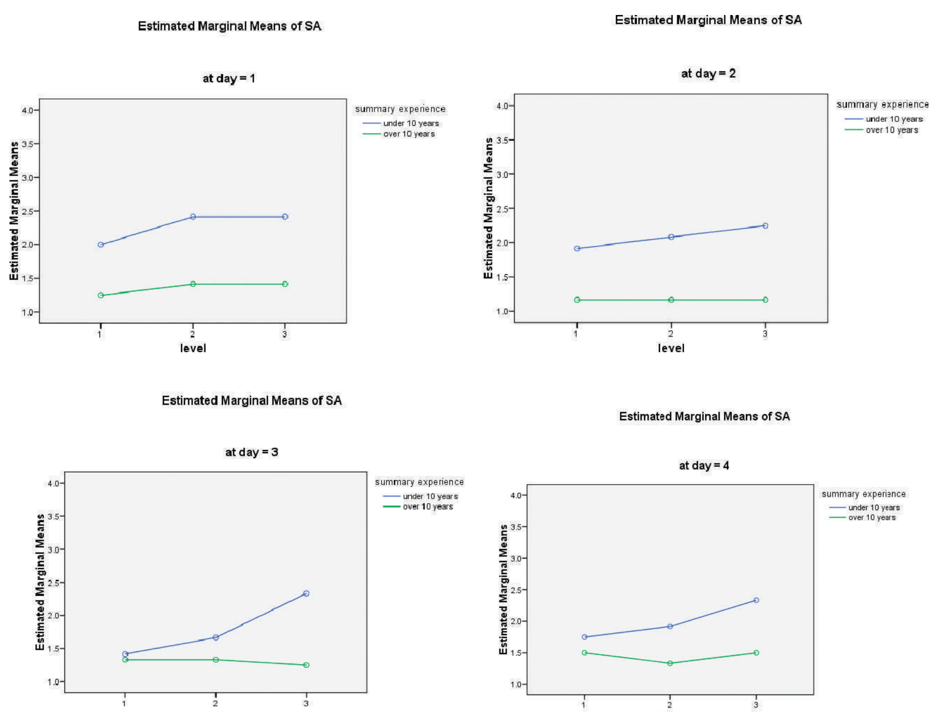

Figure 12. Reported levels of situational awareness of 4 days of trials.

The nature of networked communication and sensor technologies required the tactical leader to be aware of the unique contribution of each system to the mission. He also needed to understand the dependencies between systems and between those systems and the network. Given the combination of air and ground sensors and communication types, this was not an insignificant task. This experiment clearly demonstrated the need for the tactical leader in a networked unit to manage the network architecture for optimal system and soldier performance. Such a requirement cannot be managed by static tactics, techniques, and procedures (TTPs) alone given the dynamic nature of system and network performance in the context of terrain and unit configurations. For soldiers to gain maximum benefit from networked technologies, these systems need to be deployed in an optimal configuration *in the context of the mission*. The role of Network Manager NCO would provide services to the force such as field interpretation of system specifications for optimal use. For example, unmanned and unattended sensors have unique requirements for network support. When planning for placement of unattended ground sensors (UGS) or routes for UAS/UGVs, network connectivity is a primary factor. Also, perception of network health is critical for manned and unmanned teaming and selection of communication mode. For example, in low bandwidth conditions, text communications may be favored over voice or sharing imagery. System integration features are also a necessary consideration for successful network-enabled performance at the tactical level. Questions a Network NCO might consider include: How are systems connected? What are individual and composite system capabilities and limitations? How does the use of one system impact another system? What is the link status of network nodes? How is node drop-off or re-connectivity signaled? How can network problems be diagnosed and repaired? How can errors be diagnosed as human error (and subject to training solutions) or technology failures? These issues will be the subject of a future research effort as we attempt to harness network architectures and performance for tactical soldiers' benefits.

The UBC vision recognizes a need for dissimilar units to interoperate with organic battle command systems and share common geospatial data. The UBC-CIS study examined the ability of soldiers to interact with three different battle command systems for ISR missions against an adaptive and resilient enemy force. Though the analysis procedures were limited by the small number of subjects, this investigation provides a good insight into soldier performance results and analysis methodologies for exploring the cognitive impact of new technologies in a mobile ad hoc network environment. In addition, the advanced capabilities demonstrated by the M&S team allowed the live participants to interact with data simulating two Brigade Combat Teams, thus expanding the tactical perspective.

The workload measures document that the soldiers generally had low workload scores. Though the less experienced soldiers did report slightly higher difficulty with these tasks, they reported, on average, that this was not a particularly demanding task. This is due, in large part, to the effective use of unmanned technologies provided to the soldiers for this experiment. The coordinated use of air and ground vehicles and unattended ground sensors allowed the soldiers to maintain an awareness of enemy activity in the area of operations. This integration of manned and unmanned teaming for ISR highlights the major contribution of the Cognitive Impact Study.

This study represents the authors' efforts to plan, execute, and analyze complex instrumented and human performance data in the context of the system-of-systems demonstrated in this experiment: Network, Systems, and Cognitive. This analysis capability was made possible by the focused contributions of the entire PM C4ISR OTM experimentation and data collection staff, and required a complex set of instrumentation capabilities, data reduction methodologies, human data collection staff (to observe and administer human performance surveys), and senior researchers on site to match network, system, and cognitive performance metrics to observed behavior. This triangulation of data analysis methods provided a quantification of human performance in the context of network and system performance. These insights are valuable as mobile ad hoc networks become available for tactical units. These networks are designed to be accommodating to network disruptions and will have self-healing capabilities. Engineering these networks to optimize human performance in decision-making areas has been shown in this experiment to be possible under less than 100 percent bandwidth conditions. That the soldiers could perform well in significantly degraded video conditions suggests that limited bandwidth can accommodate decision making for certain task scenarios.

The availability of a technology such as GEC2O is the critical underpinning of this analysis activity. This technology allowed after action playback/play-forward of mission runs with archival review of messages, spot reports, and sensor images. Thus, the analysis team was able to retrieve SALUTE reports and objectively contrast the content of each message with actual instrumented activity. This capability significantly

reduced the need to record detailed activity notes on the part of observers and solved the problem inherent with field experiments of this type and duration: remembering and distinguishing between events of one day and another.

The final contribution of this study was to document the ability of soldiers to conduct planning, execution, and analysis tasks in ISR scenarios with a range of unmanned systems, communications technologies, and battle command systems. That these disparate battle command systems could be engineered in a mobile ad hoc network was a feat of merit in itself; the additional fact that the soldiers could adaptively work between these systems was of particular interest. The soldiers combined their experience with personal and Army computers with a range of classroom and field training in preparation for the field experiment and performed with low workload and high situational awareness against an adaptive enemy force.

This analysis investigated the strength of the theoretical underpinnings of the UBC vision. The methodological approach of an integrated analysis of a system-of-systems MANET represents a pioneering first step toward the goal of network optimization for human understanding in a mission-relevant environment. This method showed promise in mapping performance metrics on behavior across the network levels. Future efforts will focus on the continued resolution of quantifiable quality of service metrics, system performance characteristics, and human decision making. ❑

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Endnotes

[1]Network-Centric Warfare is also commonly referred to as Network-centric operations or Network-enabled operations. For ease of discussion, we will use the NCW term in this article to generically refer to the concept that the network is providing information communications technologies to Warfighters.

[2]Forces use the FBCB2 Blue Force Tracker capability to navigate when mobile. A 1-minute COP update rate would have the following impact: a vehicle traveling 20 mph would cover .5 miles in 1 minute. This could be an acceptable update rate or not, depending upon the nature of the navigated terrain. Such a rate would clearly be inadequate for city or village navigation.

[3]CERDEC enhancements to the FBCB2 display included windows to provide chat, sensor image links, and a view of network health status of all vehicles in the network. These enhancements were made by linking additional programs to the display.

[4]GEC2O was developed by Mechdyne, Future Skys, and JB Management at the direction of the U.S. Army CERDEC C2 Directorate. GEC2O was used in this study as a tool for replaying the missions in order to effectively understand the sequence and timing of events, which assisted in scoring SA measures.

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